CAAP Quarterly Report

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Prepared for: *U.S. DOT Pipeline and Hazardous Materials Safety Administration*

Contract Number: 693JK32050004CAAP

Project Title: Probabilistic Performance Modeling and Optimum Maintenance Planning of Plastic Pipeline with Piezoelectric Based NDE Updating

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For quarterly period ending: 9/1/2020 - 11/30/2020

Business and Activity Section

(a) Contract Activity

The subcontract to University of Akron need be changed to Marquette University since Dr. Qindan Huang (Co-PI) has changed the institution after the proposal was submitted. The PI will submit the request of change to PHMSA and process the subcontract after the approval.

(b) Status Update of Past Quarter Activities

The project kick-off meeting of this project was conducted on Nov. 18, 2020 remotely. The PI gave a presentation on the overall project objective and scope with some discussions. The attendees include Joshua Johnson (PHMSA project manager), Dr. Hao Wang, (PI), Dr. Qindan Huang (Co-PI), Lukai Guo (postdoc), and Pengyu Xie (PhD student).

The research team conducted the task of literature review and summarized the review results related to the project topics.

(c) Cost Share Activity

Cost share is provided during this quarterly period as budgeted in the proposal.

(d) Technical Approach

Literature Review Report

1. Plastic Pipeline Failure and Non-Destructive Testing

1.1 Performance Degradation and Failure of Plastic Pipeline

Plastic pipelines can be damaged due to two types of reasons. First type of reasons is from external conditions of pipeline, such as operational circumstance, manufacturing defects, soil settlement, or mistakes during installation and operation. Those reasons can cause discrete amounts of the pipeline's capacity to be dropped at distinct points due to sudden and independent events. Another type of reasons is mainly from degradation of plastic material properties, due to material aging and chemical effect of transport fluid. Given basic material properties of plastic polyethylene (morphology and molecular mass), the physical or chemical aging can cause crystallinity, crosslinking, or degradation of plastic material itself. Those material property changes can further be reflected by slow variations of mechanical properties in long term (Arbeiter et al., 2009), such as increased elastic modulus, raised hardness, and reduced fracture resistance (Tavares et al., 2003). Those progressive degradation process can continuously and infinitely reduce the pipeline structural capacity over time.

From the perspectives of mechanical failure modes, the pipeline degradation process can be represented by ductile rupture (DR), brittle failure due to rapid crack propagation (RCP), and quasi-brittle failure due to slow crack growth (SCG) or creep crack growth. The reasons causing above mechanical failure modes are different: DR is formed by high internal pressure; RCP is developed from an initial axial notch in the pipe wall with large driving force against fracture resistance of plastic; SCG is first created by slow-growing brittleness of the pipe and deteriorated by inclusion, contaminants, scratches, and so on (Maupin and Mamoun, 2009).

To better predict the pipeline failure with time, Gas Technology Institute (2009) developed a Rate Process Method (RPM) with the Bi-directional Shift Functions (BDSF) to predict the expected service life of PE pipeline using long-term hydrostatic stress-rupture data. The Rate Process Method did well in describing the relationship between hoop stress and failure time, as shown in Figure 1.

For the counter-measurements against those failure modes of plastic pipe, based on their causing factors, DR and RCP can be avoided by proper pipeline operation (e.g., proper internal pressure control) and extra pipeline protection (e.g., notch prevention), while SCG cannot be fully avoided in a long term. As shown in above Figure 1, with exhibiting little material flow or deformation, the performance degradation in plastic pipeline caused by SCG at region B is difficult to be detected from routine and visual inspections until critical failure happens at region C (Arbeiter et al., 2009). A more efficient inspection method for accurately and continuously monitoring the performance degradation of plastic pipeline is required. That is the major objective of this project to explore a new NDT test relying on piezoelectric effect, instead of using optical methods.

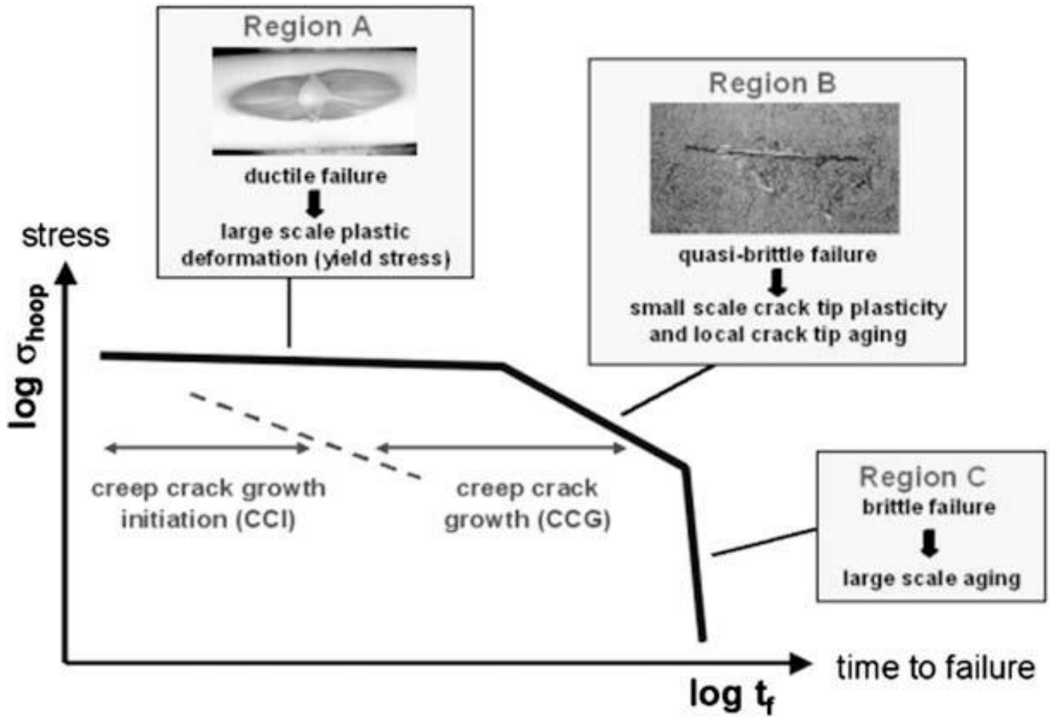


Figure 1 Scheme of failure behavior of plastic pipes (Maupin and Mamoun, 2009)

Considering the significant effect from temperature on pipeline degradations, the original RPM and BDSF were further modified by adding Temperature Factor (TF), as shown in Equation 1.1. As major findings from that project, it is stated that the rock impingement loads and pipe squeeze-offs can significantly shorten the service life of pipe, while the lower field temperature and pressure can slow the SCG development on the pipe (Maupin and Mamoun, 2009). For avoiding RCP, critical pressures (ranging from 11.5 psi to 27.6 psi) and critical temperatures (ranging from 36.9 °F to 65.5 °F) were determined in that study. Moreover, series of conventional tests were tried to detect the SCG failures by measuring PE material properties, such as melt index, tensile strength, quick burst, PENT, and bend-back tests. The PENT test refers to ASTM F 1473 "Standard Test Method for Notch Tensile Test to Measure the Resistance to Slow Crack Growth of Polyethylene Pipes and Resins". Among those tests, only bend-back tests did successfully identify the aging of low-ductile inner wall materials (Maupin and Mamoun, 2009).

$$\log_{10} Time = A + \frac{B}{T} + \frac{C \log_{10} P(TF)}{T} \tag{1.1}$$

Where, "A", "B", "C" represents unknown constants, which are functions of the material properties, temperature, stresses or applied loads, and geometrical variables; "T" is the

absolute temperature in Kelvin; “P” is the pressure; “Time” is the average failure time corresponding to T and P; TF is the temperature factor, equals to 2 if the temperature is lower than 50 °C, or equals to 1 if the temperature is higher than 50 °C.
For observing the temperature effects on changing mechanical property of plastic pipeline, Tavares et al. (2003) placed a polyethylene sheet ($10 \times 10 \times 0.1$ cm^3) into the Weather Tester (QUV) and weatherometer (WOM) chamber to accelerate the aging process. The specific mechanical properties, including surface hardness and elastic modulus, were measured through nanoindentation technique using a hard pyramidal tip. As results, it was found that, as the aging developed, the overall hardness of polyethylene sheet increased from 0.02 GPa to 0.08 GPa, while the elastic modulus of the sheet increased from 0.4 GPa to 1.9 GPa in average (about 2.2 GPa in QUV and 1.6 GPa in WOM).

Laiarinandrasana et al. (2011) studied the aging effect on creep behavior and residual lifetime assessment of plastic pipeline via residual lifetime assessment with finite element modeling results. With using the fracture mechanics for creep solid (FMCS) tools, the resistance to creep failure of plastic pipes was predicted. As the results of master curves from creep tests on both undamaged and cracked specimens, it was found that the creep time to failure had good correlation with the crack opening displacement rate, while aging reduced the displacement rate. However, aging was not a key factor to affect the relationship between load and creep time to failure (Laiarinandrasana et al., 2011).

Another recent study was conducted by Arbeiter et al. (2014) to observe the SCG failure mode of plastic pipe. They conducted cyclic cracked round bar (CRB) specimen tests on a polypropylene pipe to simulate the quasi-brittle failure mode. For accelerating the testing process, higher temperatures, 50 °C and 80 °C, were used during those CRB tests. Based on the comparison between brittle failure from the field sample and from the CRB-tested sample, it was confirmed that the cyclic CRB test was able to create the quasi-brittle cracks that were close to the ones observed in the field. Since the quasi-brittle cracks were difficult to be observed and quantified by regular measurement techniques, scanning electron microscopy was used to track the quasi-brittle failures (Arbeiter et al., 2014). As a major finding from that study, both block-polypropylene material (PP-B) and high density polyethylene material (PE-HD) show a linear trend between the applied stress intensity factor (K_1) and the loading cycles to failure (N_f) for quasi-brittle failure in a double-logarithmic diagram ($\log(K_1) \sim \log(N_f)$). The specific slope of this double-logarithmic diagram was found also varied by testing temperatures (e.g., 23 °C, 50 °C, and 80 °C) (Arbeiter et al., 2014).

Given the both discrete and continuous performance drops involved by failure process of pipeline, Amaya-Gómez et al. (2019) used In-Line Inspection Tool to measure the inner and outer pipeline thickness and calculate the depth increment for formulating a pipe degradation model. Combing Gamma and Compound Poisson Processes (called a Mixed Lévy process), the degradation process of pipe was described based on the ILI data. After the parameters of degradation process was determined to build the corrosion degradation model, an integrity assessment based on the Mean Time to Failure (MTTF) was performed. As results from the integrity assessment, leak-prone segments of the pipeline were identified (Amaya-Gómez et al., 2019). Although steel pipeline corrosion was focused in this study, the performance modeling approach can be adopted for other applications.

1.2 Non-Destructive Evaluation of Plastic Pipeline

The traditional pipeline inspection approaches rely on visual inspection or physical testing of pipe sections for anomaly detection. These approaches are usually destructive and require frequent onsite visits. An alternative way of inspection is to use non-destructive evaluation (NDE) techniques, such as eddy-current (Kim et al., 2004), magnetic-particle (Shi et al., 2015), advanced visual testing (Lever, 2017), and ultrasonic (Ghavamian et al., 2018) methods. However, many NDE methods can be only applied on metal pipelines, since they require the surface material of pipeline being electric or magnetic conductive.

Plastic pipelines are more commonly inspected through either visual testing method or ultrasonic method. Visual testing method relies on the images captured by camera and analyzed via image processing techniques, in addition to using human eyes and subjective measurement. The optical sensing imaging method has been studied in previous project sponsored by PHMSA to identify and quantify the defects on inner walls of small plastic pipes, such as crack, bump, dent, hole, split, and squeeze (Lever, 2017). However, the material-related failure modes, such as embrittlement and strength decay, cannot be detected through the optical-based method. Moreover, operating such optical-based NDE technique needs shut-down of pipeline; and thus, the inspection frequency is limited, which could cause the failure potential underestimated. Therefore, it is desired to develop new sensing techniques that can continuously monitor plastic pipelines and detect cracks along with the degradation of material properties.

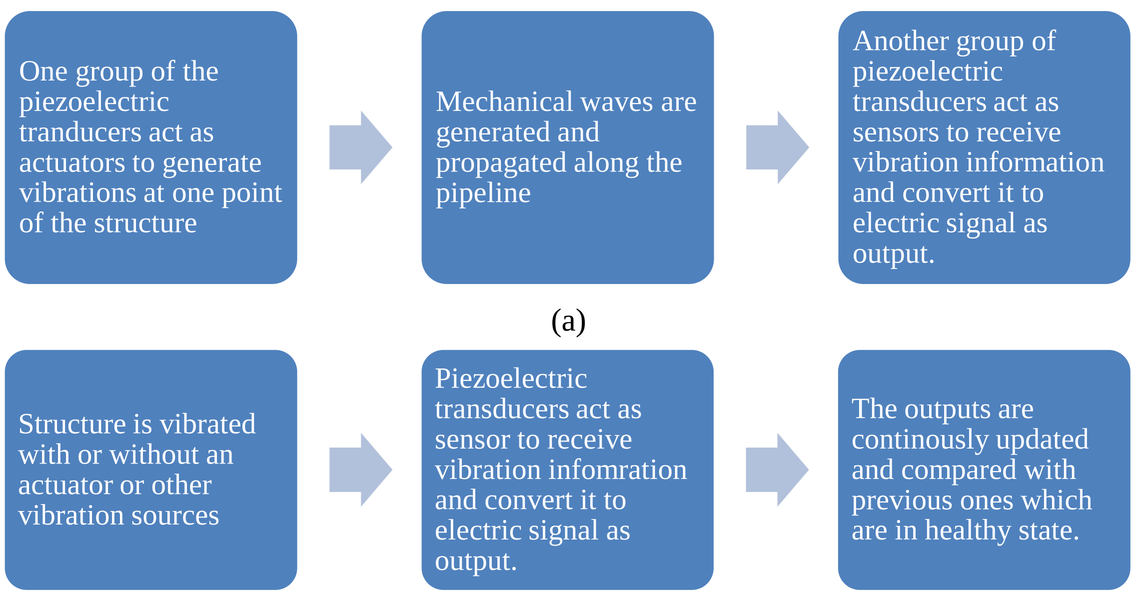
Ultrasonic method relies on guided wave generated by an actuator and propagated along the pipeline. Any features changing the pipe geometry and defects can be detected by the variations of waveforms received by sensors (e.g., partial reflection, signal intensity). Previous studies have proved its feasibility to detect pipe geometric features (Zhuang et al., 1997), corrosion (Løvstad, 2012), or crack (Demma et al., 2003; Valle et al., 2004; Fletcher et al., 2012). Electro-mechanical impedance (EMI) technique is an alternative method, relying on the same equipment (actuators and sensors) but based on different principles and analysis methods. EMI utilizes the fact that the impedance of pipeline is affected by the defects in the pipeline and the sensors can capture the variation of such impedance. The feasibility of using EMI technique to monitor pipeline structure (specially to target crack location inside the pipeline) has been proved by previous studies (Park et al., 2001; Zuo et al., 2017; Yan et al., 2018).

Although NDE-based inspection can provide valuable information for performance perfection and maintenance planning, the reliability and accuracy of NDE for inspection of plastic pipes still need to be quantified and improved. For example, the probability of detection and measurement error of crack size from NDE should be appropriately quantified. On the other hand, the NDE data should be used to properly update performance prediction of the structure. For example, when using Paris' law to model SCG of plastic pipeline, the material related model parameters are very sensitive. Therefore, the model parameters for the time-evolution of crack and the degradation of material properties need be updated to reduce uncertainty of performance prediction, when NDE data becomes available.

2. Piezoelectric-based NDT for pipeline condition evaluation

2.1 Types of Piezoelectric-based NDT

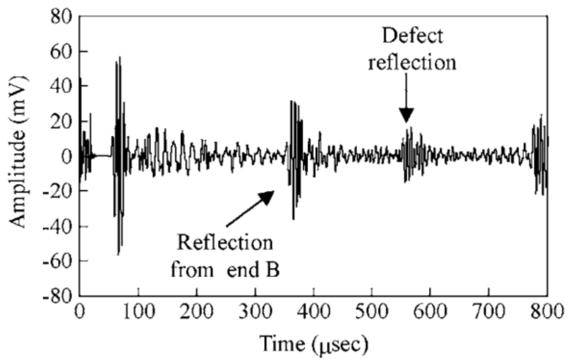
There are two major structural monitoring approaches via piezoelectric effect. One is based on wave propagation along the pipeline. Once the wave reaches any defects related to pipeline deformation, reflection waves will be generated and the specific location of the defect can be calculated via the time of flight method (Yan et al., 2018; Crane et al., 1997; Gao et al., 2009; Bareille et al., 2012; Rizzo et al., 2005). Another one is based on impedance changes at individual points on the pipeline. Once any defect occurs on the pipeline, it will affect the impedance of points on the pipeline, especially for the ones closing to the defects (Park et al., 2001, Peairs et al., 2004; Thien et al., 2008; Baptista et al., 2010; Wang et al., 2020; Na and Lee, 2012). The major difference between those two methods is the selection of reference signal. For wave-propagation method, the reference signal is the one from actuator before it is propagated to the receiver; while for impedance-based method, the reference signal is the one from sensor under undamaged state of the pipeline. The detailed processes from those two methods are illustrated in Figure 2 for comparison purpose.



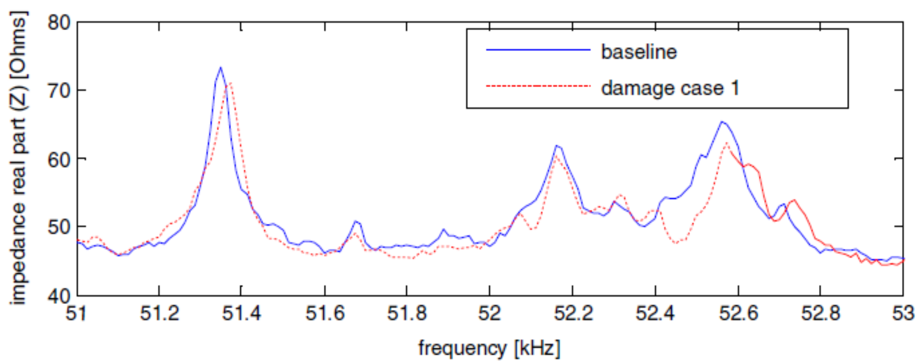
(b)

Figure 2 Flowchart of a) process of wave-propagation based method; b) process of impedance-based method

Figure 3 displays typical signal forms from two piezoelectric-based NDT methods. As can be seen, due to the different analysis methods, the initial signals used for analysis in wave-propagation based method are well-designed waves in time domain, while those analysis signals for impedance based method are after Fourier Transform in frequency domain. For wave-propagation based method, the location of defect can be calculated by reflected waves based on single wave signal. However, for impedance-based method, the location of defect cannot be obtained based on single wave signal from one transducer. Multiple wave signals from a series of transducers are needed. For quantifying the severity of defects or even classifying the specific defects, advanced signal processing and machine learning techniques are usually needed.



(a)



(b)

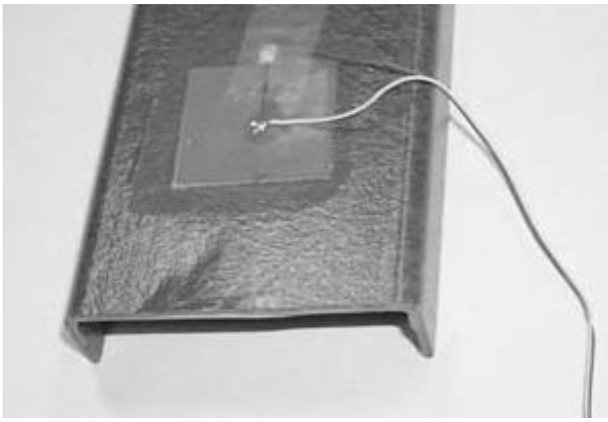
Figure 3 Typical signal forms from a) wave-propagation based method (Rizzo et al., 2005); b) impedance-based method (Thien et al., 2008).

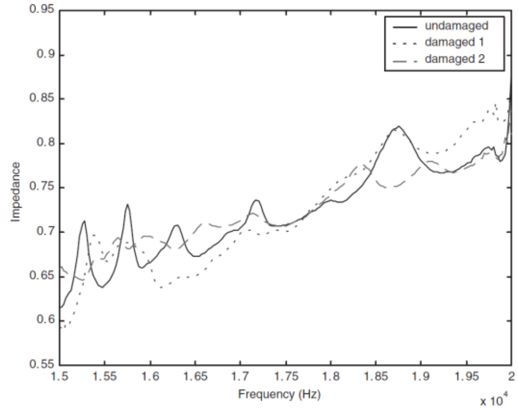
2.2 Piezoelectric-based NDT on different pipeline structures

Piezoelectric-based NDT has been successfully applied on both steel (Park et al., 2001; Peairs et al., 2004; Bu et al., 2007; Thien et al., 2008; Baptista et al., 2010; Guo et al., 2019; Huan et al., 2020; Wang et al., 2020) and plastic (Gao et al., 2009; Ahadi and Bakhtiar, 2010; Bareille et al., 2012; Hong et al., 2017) pipelines in different designs and structures. In general, the earlier studies focused on the piezoelectric-based NDT on the steel pipeline because of its low damping property leading to a long-distance coverage. However, more recent studies have confirmed the feasibility of using piezoelectric-based NDT on plastic pipelines. Although high damping from the plastic pipeline can attenuate the wave signal and shorten the monitoring coverage, it can also make the signal more easily for analysis due to less reflections, especially on complicate pipeline structures (Bareille et al., 2012).

Park et al. (2001) proved the feasibility of using the impedance-based health monitoring method on steel pipeline structures (Park et al., 2001). They set $15 \times 15 \times 0.2$ mm PZT wafers on the joint of one pipeline system. Each pipeline segment set in the laboratory was made by steel, with 1-m length and 40-mm diameter. All those PZT wafers were connected by one lead to get one single signal for further multiplexing analysis (Park et al., 2001). That single voltage signal was collected by a HP4194 electrical impedance analyzer for measuring the electrical impedances of those PZT wafers. A proper operational frequency ranging from 80 to 100 kHz was found by trial-and-error method. Such detailed frequency range was chosen due to 20 – 30 peaks found within that range, which provided more structural dynamic information for better detection and categorization purposes on pipeline damages (loosening bolts) (Park et al., 2001). After observing the impedance changes before and after loosening bolts, they found that a group of PZT wafers could detect such damages within a range where the impedance was affected. This finding shows the feasibility of using multiple groups of PZT wafers to target the specific damage location or point, while also reflects a sufficient number of PZT wafers are required to cover the effective detection area by those PZT wafers. However, they did not test this method on detecting other types of damage, nor propose a way to identify different damage categorized based on the impedance changes. The effective detection area could also be more limited if the pipeline is made by plastic rather than by steel, considering much higher damping from plastic materials (Park et al., 2001).

To verify the feasibility of using PZT-based impedance measurements on structural health monitoring purpose for different materials and structures, Peairs et al. (2004) placed PZTs on multiple structures, including bolted joint, gas pipeline, and fiberglass beam (see Figure 4(a)). They confirmed this low-cost PZT-based method was an alternative solution over the more expensive one, using an impedance-measuring device, HP4194A, to give the same impedance measurement results. Those PZTs were driven by 1 V peak chirp signal from a DSPT SigLab^{TM} dynamic signal analyzer (DSA). For fiberglass beams, they found that the impedances were overall increased by elevating the frequency, due to the damping from composite structures, as shown in Figure 4(b). However, the impedance changes were still clearly observed over accumulating damages (cracks). This finding reflected the potential of using PZT-based impedance measurement methods on health monitoring materials with high damping (Peairs et al., 2004).





(a) (b)

Figure 4 (a) PZT patch on a high-damping composite beam with damage near the patch; (b) Impedance measured by damaged and undamaged composite beams (Peairs et al., 2004).

A few studies have used piezoelectric-based NDT to monitor the condition of plastic pipelines. Gao et al. (2009) studied the effect of wave reflections on detecting the leakage on plastic pipeline through either vibration or acoustic signal collected by either acceleration or hydrophone. The generalized cross-correlation (GCC) phase transform (PHAT) was applied to remove the reflections and the low-pass filter. Although researchers developed the theoretical model fitted either vibration or acoustic signal, the feasibility of such techniques on leakage detection was only verified using hydrophones as sensors during field tests on buried plastic water pipes in Canada. That study also found that, the reflections significantly affected the cross-correlation function for detecting purpose if the pipeline had low damping or the sensors were close to the leakage. However, if the pipeline had high damping or the sensors were far away from the leakage, the cross-correlation function for detecting purpose turned to be more affected by the filtering properties of the pipeline (Gao et al., 2009).

Ahadi and Bakhtiar (2010) utilized short time Fourier transforms (STFT) of acoustic emission signals to detect the leakage in a water-filled plastic pipe. The original captured signal was then processed to get turned wavelet analysis for targeting the leakage signal-signatures from other interfering signals. As the major finding from their study, acoustic emission signals can be used to detect and identify the leakage location precisely. In their experiments, the acoustic emission signals were received by a piezoelectric hydrophone with a bandwidth of 10 kHz, which was suspended inside the pipeline. A low-noise amplifier was connected with the hydrophone to amplify the analog signal. For identifying the leakage with other interfering signals, the signals from background noise, splash noise, and leakage were separately recorded and analyzed by wavelet transforms, as shown in Figure 5 (a) and (b). After the feature of leakage signal was recognized through the STFT of the sliding short time windows, search among the tuned wavelets was successfully performed for detecting and quantifying the leakage, as shown in Figure 5 (c) and (d) (Ahadi and Bakhtiar, 2010).

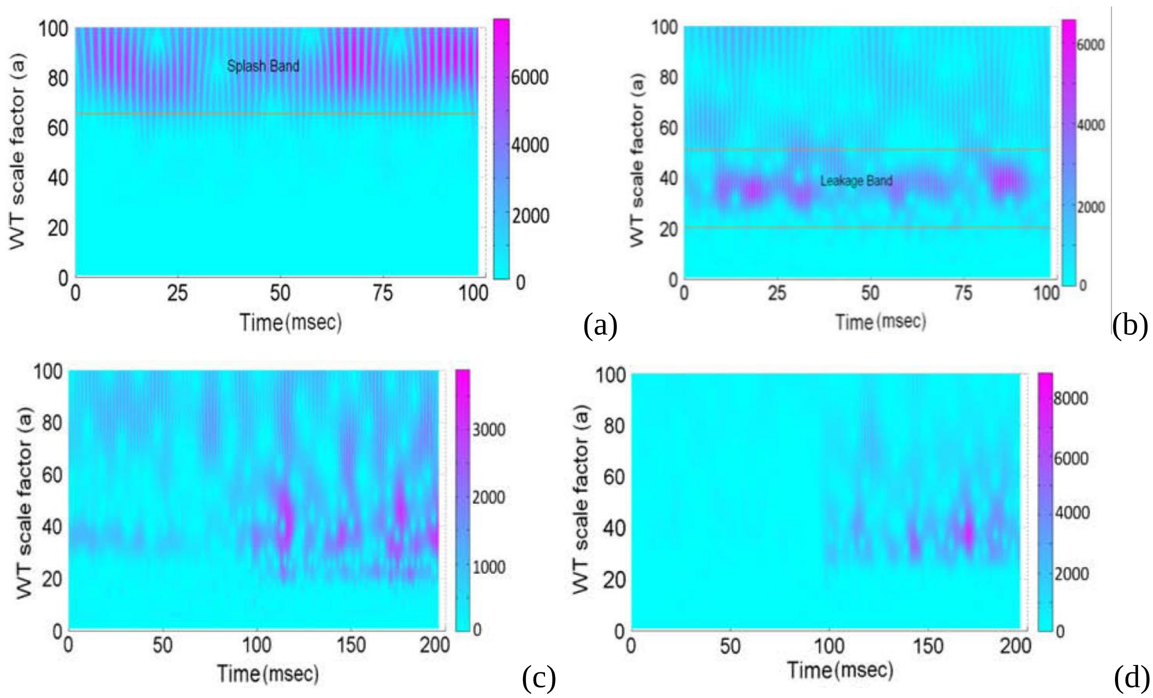


Figure 5 Spectrogram of WTs of: (a) splash and background noise AE; (b) leakage AE; (c) the signals measured with leakage size of 2 mm; (d) the signals measured with leakage size of 4 mm (Ahadi and Bakhtiar, 2010).

Bareille et al. (2012) proposed a piezoelectric guided-T-wave generator to produce torsional wave for health monitoring on both plastic (polyvinyl chloride, PVC) and steel pipelines. Instead of using a piezoelectric continuous ring to create shear strains via high d_{15} performance, they attached numbers of piezoelectric patches to the pipeline to create local torsional movement along the outrebound of the pipeline. The most important reason why the researchers did select plastic pipeline in part of their study was because of the damping from plastic pipeline. Due to the high damping, no reflection from the end of the pipeline could be detected by the sensor if the sensor was set further than the middle of the pipeline. A typical signal received from piezoelectric transducer on plastic pipeline was displayed in Figure 6. As can be seen from Figure 6, without the portion of reflection wave, the received signal was surely incident wave, which was more easily analyzed and better treated as a reference for simulation purpose. Moreover, they confirmed that the torsional wave was still able to detect and locate the crack through the reflection from the defect's location, although high damping from a plastic pipeline can weaken the wave amplitude (Bareille et al., 2012).

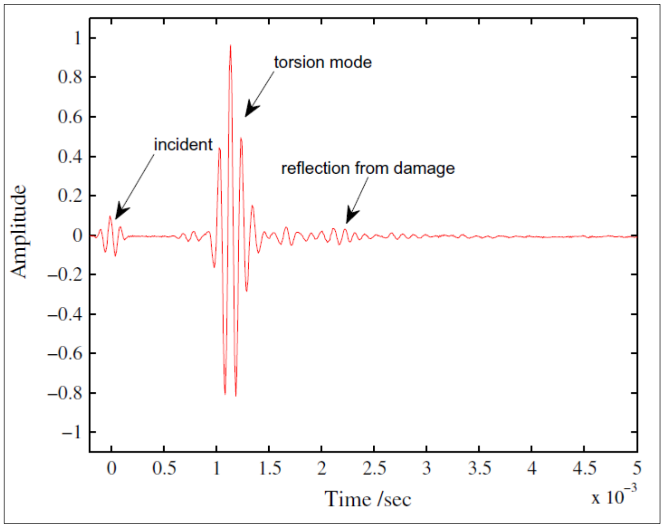
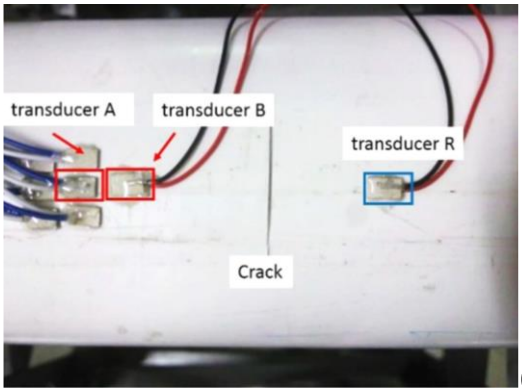
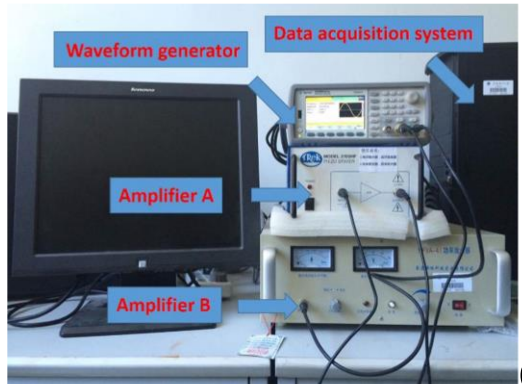


Figure 6 Time signal recorded with defect on PVC pipe (Bareille et al., 2012)

Hong et al. (2017) used PZTs as actuators and sensors on a plastic pipeline system for detecting crack damages on it. Instead of using Lamb wave or impedance method, they applied the wavelet packet analysis to get the wavelet energy of signals from PZT sensors for health monitoring purpose. Prior to the signal analysis, the signals received by PZT sensors were first processed through being filtered, synchronous demodulated, and modified by a proposed mean equalization method. The length, inner radius and outer radius of polyvinylchloride pipeline were respectively 1.5 m, 50 mm, and 53 mm. There were three PZT transducers attached on the pipeline by Loctite epoxy. Two of them were actuators connected with waveform generator and amplifiers to generate vibrations individually at high frequency (150~180 kHz) and low frequency (5~15 kHz), while another of them was a sensor to detect the response signals and import the data into a data acquisition system (Hong et al., 2017), as shown in Figure 7(a) and (b). One crack was created between those two actuators and one sensor. It was developed from 0 to 35 mm length and 0 to 2.5 mm depth. As results, it was found that the wavelet energy decreased as the crack grew. The signals in high frequencies played more important roles on this wavelet packet analysis than those in low frequencies. However, the accuracy of this method on detecting and quantifying the cracks still needs to be confirmed (Hong et al., 2017).



(a)


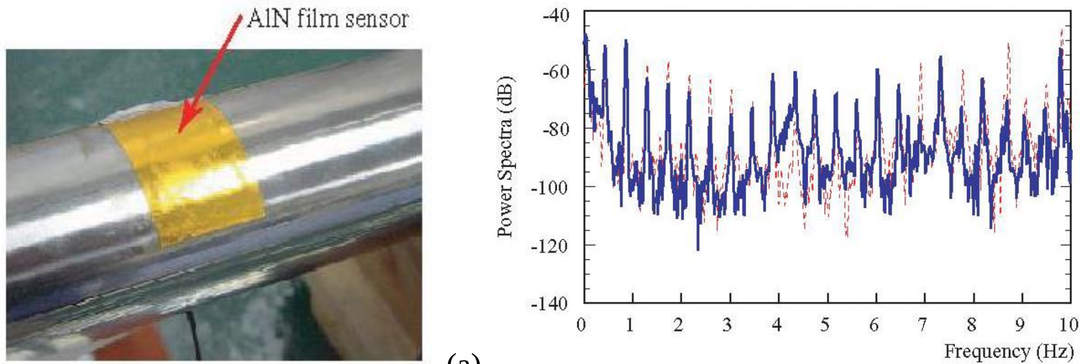
(b)

Figure 7 (a) Transducers set on plastic pipeline; (b) Signal generation and collection devices

2.3 Piezoelectric-based NDT using different piezoelectric transducer designs

Given different piezoelectric transducer designs can create various types of waves for health monitoring purpose, multiple recent studies focus on the special piezoelectric transducer designs for improving health monitoring performance. Although most of previous studies focus on the steel pipeline, the ideas from those piezoelectric transducer designs can still partially be implemented on plastic pipelines in further studies.

To improve the flexibility of the piezoelectric sensors with remaining their acceptable piezoelectric performance, Bu et al. (2007) proposed a sensor made by two layers of oriented aluminum nitride (AIN) thin films and two layers of polyimide films (Bu et al., 2007), as shown in Figure 8(a). Since AIN can remain its piezoelectric performance under a high temperature up to 1150 ℃, this sensor will be more stable than the PVDF-based sensor (temperature limitation is 80 ℃) if the pipeline carries heat fluids. Considering the low stiffness, all AIN sensors used in this pipeline health monitoring system did not act as actuators, but only on sensing purpose. The size of each AIN sensor had coverage area of 20×30 mm^2, with total thickness of 40 μm (Bu et al., 2007). The tested pipeline was made by stainless steel in an external diameter of 38.1 mm. The signals generated by AIN sensors were input into a charge amplifier, 2692-A-0S4 from Brüel & Kjæl, and then acquired with a 14-bit A/D converter, USB-6009 from National Instruments. Since no actuators involved in this system, the vibration of pipeline was triggered by flowing water. Once a blockage occurred in the pipeline system, the flow velocity was changed due to the Venturi effect and fluid reflection. Such unusual flow velocity change did further cause a pressure pulsation, which was successfully detected by the AIN sensors, as shown in Figure 8(b). Besides detecting the pipeline blockage, authors also expect to use these AIN sensors to detect cracks and corrosions via the same system in the future research (Bu et al., 2007).



(a) (b)

Figure 8 (a) AIN film sensor attached on the steel pipeline; (b) Power spectra of filtered signals of AIN film sensor with (in blue color) and without (in red color) blockage.

Considering the flexibility and stiffness of piezoelectric micro-fiber composite (MFC), Thien et al. (2008) tried MFC sensors with both health monitoring methods (impedance-based and Lamb wave-based ones) on steel pipeline structure. The MFC used in that study was M8557, in an overall dimension of 110×75 mm^2, provided by Smart Materials Inc. For lamb wave-based method, to create and receive Lamb wave, it required totally eight MFC patches mounted around the circumference of the pipeline. Half of them formed as one ring for actuating purpose at one location, while another half of them formed another ring for sensing purpose at another location. The signal generation and collection were both performed by a portable data acquisition system (Thien et al., 2008).

For achieving high voltage outputs to actuate the MFC patches, an external power amplifier was first connected to the MFC. An excitation frequency of 70 kHz was selected to identify different wave propagation modes. For impedance-based method, instead of using four MFCs on each of two locations, each single MFC was selected at each of four locations along the pipeline. An Agilent 4294 impedance analyzer was connected with the MFCs to measure the local impedances under frequency ranges from 50 to 60 kHz and 110 to 120 kHz (Thien et al., 2008). The impedance measurement changes before and after damages at multiple locations were used for quantifying and locating the damage. As one major finding from that study, it was observed that the impedance-based method was better to detect loosened joints, while the Lamb-wave-based method was better to detect crack and corrosion damages (Thien et al., 2008).

Given PZT transducers in different sizes have different electrical impedance, the size of PZT transducer can affect the detailed frequency selection and the measurement accuracy for impedance-based health monitoring procedures. For studying the effect of PZT sizes on health monitoring performance, Baptista et al. (2010) attached square PZT patches in different lengths (from 5 mm to 80 mm) by superglue on different aluminum specimens (beam, plate, and plate with a patch). The electrical impedances of those square PZT patches made by 5A and 5H were measured by a DAQ USB-6259 from National Instruments. The operational frequency for measurement was within 62.5 kHz with a resolution around 2.38 Hz (Baptista et al., 2010). The damage indexes, both RMSD and CCDM, were calculated based on the electrical impedances measured under undamaged and damaged conditions. As results from that study, it was found that the size of PZT patches shall be proper to ensure low static capacitance and high amplitude in the electrical impedance to get clear results of RMSD and CCDM indexes for health monitoring purpose. Meanwhile, an increased size or number of PZT patches shall match a larger host structure to improve the sensitivity of PZT impedance changes against pipeline damages (Baptista et al., 2010).

Instead of using PZT or MFC as actuators and sensors for health monitoring the pipeline, Guo et al. (2019) coated the PVDF polymer on a steel pipeline to generate and detect the guided waves for pipeline damage detection, related to local thinning. The whole system with some representative signal results are displayed in Figure 9. The thickness of PVDF coat was around 25 μm. The guided wave was a Lamb wave in L(0,3) mode under 260 kHz. Each electrode on the PVDF polymer was made by silver paste, at width of 7.8 mm and length of 60 mm. The interval between two electrodes was 7.8 mm. The voltage signal to actuate the PVDF polymer was generated from a function generator, Agilent 33210A and amplified by a power amplifier, EI2100L. The voltage signal from PVDF was recorded by an oscilloscope, Tektronix TDS 3052C (Guo et al., 2019). As results, it was found that those direct-write piezoelectric transducers could not only detect trenches (with depths from 0.25 to 5 mm) through Lamb mode waves, but also measure the pipeline's wall thickness based on pulse-echo mode (Guo et al., 2019).

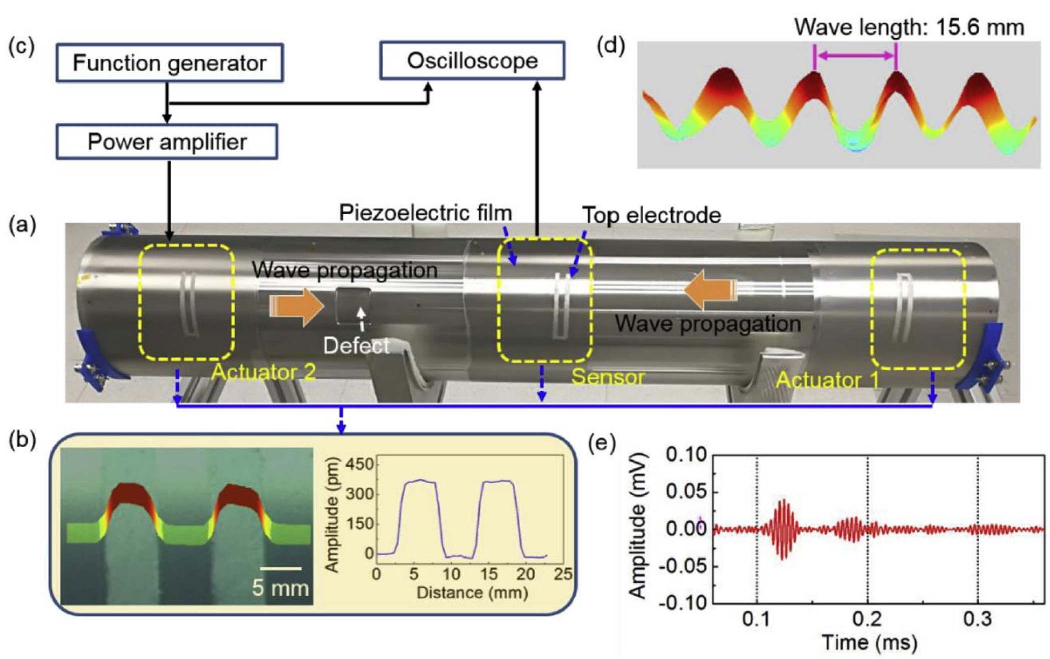


Figure 9 PVDF polymer directly coated on the steel pipe for health monitoring purpose. (a) Photograph of the steel pipe with in-situ fabricated direct-write transducers and artificial external defects. (b) The effective piezoelectric coefficient (d33) characterization using laser scanning vibrometer (LSV). (c) Other devices connected with transducers. (d) The detected ultrasonic wave at 260 kHz using LSV. (e) The ultrasonic signal detected by the direct-write transducer (Guo et al., 2019).

To explore new shapes of PZT transducers for better fitting the cylindrical structure, Huan et al. (2020) built a pair of pitch-catch T (0,1) wave piezoelectric ring array transducers for health monitoring the buried steel pipes. Instead of using the piezoelectric transducers with a same poling direction, the actuator and the receiver were respectively poled in a thickness shear d_{15} mode and a face shear d_{24} mode. The cross section of pipeline tested in the laboratory had outer diameter of 159 mm with wall thickness of 4.5 mm. The length of that pipeline was 10.62 m. The size of the d_{15} piezoelectric element was $10 \times 4.5 \times 2$ mm^3, while the size of the d_{24} piezoelectric element was $8 \times 8 \times 1$ mm^3. A through-thickness notch was built on the pipe as a circumferential defect, with a size of 30 mm in the circumferential direction and 1 mm in the axial direction (Huan et al., 2020). For the exciting wave, a five-cycle sinusoid tone burst moderated into Hanning window was generated by a function generator (3320A, Agilent), and then amplified by a gated radio frequency pulse amplifier (GA-2500A, Ritec) under a peak-to-peak voltage of 650 V. The signal received by the d_{24} sensor was recorded by a digital oscilloscope (DSO-X 3024X, Agilent) with 128 times trace averaging (Huan et al., 2020). As the major results, they found the distance of defect inspection could be 40 m for pipes with epoxy paint (EP) coating, while the distance could be shortened to be half if the pipes are coated by epoxy coal asphalt paint (ECAP). The defect locating error was fallen within a range of 0.01 m. For the selection of operational frequency, it was found that the wave attenuation was significantly increased from less than 0.1 dB m^{-1} to 0.57 dB m^{-1} if the frequency was increased from 65 kHz to 150 kHz. This finding confirms that, for a long-distance defect detection, low operating frequency (below 65 kHz) is highly recommended (Huan et al., 2020).

Similarly, Wang et al. (2020) used one piezoelectric ring circularly attaching to the outer or inner of steel pipe for respectively detecting pipe corrosion or bearing wear, as illustrated in Figure 10. Once the wall thickness of the pipe is changed due to the corrosion or wear conditions, the impedance peak and valley frequencies of the piezoelectric ring will be altered, and the signal change can be used for monitoring purpose (Wang et al., 2020). The impedance of the entire specimen was measured by an impedance analyzer under a scanning frequency range of 30 kHz to 60 kHz with an interval of 10 Hz. The scanning frequency range can neither lower than 30 kHz due to no resonance peak observed, nor higher than 60 kHz to prevent PZT rings from independent vibration. For quantifying the pipe defects, the root mean square deviation (RMSD) of the impedances was first tried as the damage index. However, it was failed due to too close values of RMSD under different conditions. As an alternative way, the resonance frequency of the specimen observed by PZT rings was recommended as a better indicator in that study for monitoring the pipe corrosion and bearing wear conditions. It was found that the first resonance and anti-resonance frequencies was correspondingly reduced as the pipe corrosion amount increased (Wang et al., 2020).

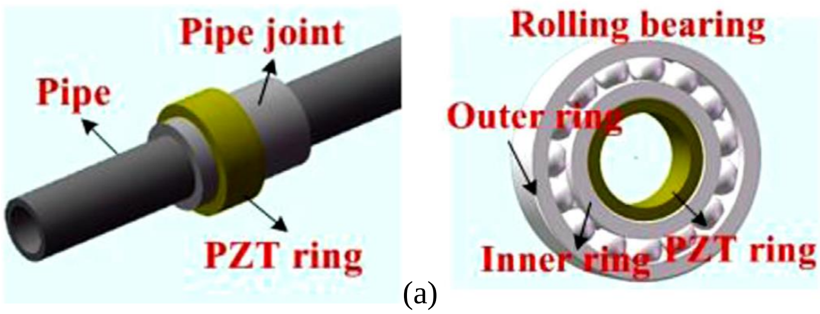


Figure 10 PZT ring on (a) outer and (b) inner of steel pipeline

2.4 Piezoelectric-based NDT with modified testing procedures

Besides trying different piezoelectric transducer designs, another "hardware" option to improve the performance of piezoelectric-based NDT on pipelines is to modify and improve the testing procedures, especially for acquiring more clear (without noise), informative (with more characteristic peaks under a proper frequency band), and continuous (with less interruption by battery replacement) signals. Most previous studies focused on metal pipelines (Choi et al., 2011; Razi et al., 2013; Cui et al., 2014; Okosun et al., 2019; Raju et al., 2020), while one of them did work on the composite beam (Na and Lee, 2012).

On the perspective of energy consumption from health monitoring systems, a traditional wireless sensing system requires high-power-consuming sensors, which challenges the continuity of detecting pipeline defects due to more frequent battery replacement on each sensor node. To save power consumption from the sensors, Choi et al. (2011) assembled PZT sensors (to replace high-power-consuming sensors), an AD5933 impedance-to-digital converter (for impedance measurement), and a Zigbee PHY(CC2420) RF transmission module (for wireless data transmission), to build a wireless low-power-consuming sensing system for pipeline health monitoring purpose. The responding impedance signals were generated by PZT sensors for detecting and quantifying the loosened bolts through damage indices calculated by the root mean square deviation (RMSD) of voltage outputs and the correlation coefficient (CC). Due to low power required by this system itself, with developing an Automatic Lifetime Manager (ALM) program, this system can operate more than 10 days with providing accurate and stable monitoring function.

The suitable frequency needed for detecting damages based on impedance method usually requires massive time from the trial-and-error approach. To shorten the time required from the trial-and-error approach and to lower the frequency range for damage identification, in 2012, Na and Lee placed one metal disc between PZT elements and a glass-epoxy composite plate (Na and Lee, 2012). Since the natural frequency of the metal disc was known and easily adjusted in different sizes, the frequency with peak of impedance for damage detection could be easily acquired within the desired and observable range, as shown in Figure 11. The feasibility of this idea was conducted by attaching a $10 \times 10 \times 0.5$ mm^3 PZT element on a $600 \times 50 \times 3.5$ mm^3 glass-epoxy composite plate, with or without a metal disk (25 mm diameter and 2 mm thickness) between them. The impedance measurement was conducted by an AD5933 evaluation board (Na and Lee, 2012). Two damages were made on the composite plate. One was a 20 mm artificial cut, and another one was a 20 mm $\times$ 50 mm debonding to the adhesive layer. As a major result from that study, it was found that the frequency range for damage identification was narrowed from 10~80 kHz to 20~30 kHz after the metal disk was added (Na and Lee, 2012).

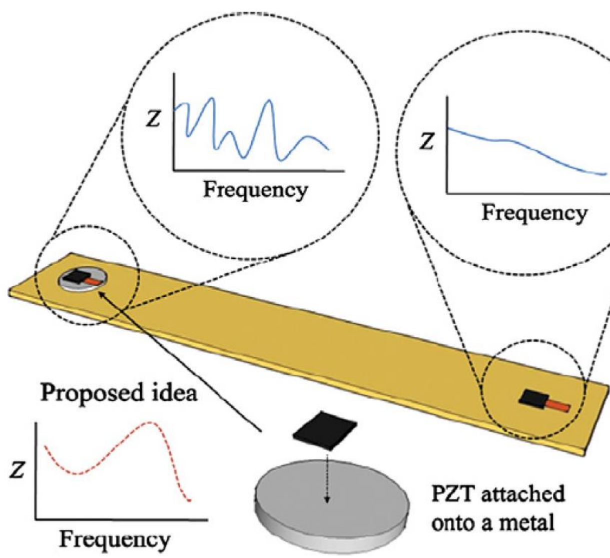


Figure 11 PZT attached onto a composite beam with or without sandwiching a metal plate with different impedance measurements (Na and Lee, 2012).

Instead of using piezoelectric actuator to excite the pipeline, applying an electric impact hammer was proposed by Razi et al. (2013) as an alternative way to create vibration signal along the pipeline for health monitoring purpose, especially on the loosening bolt. Compared to the excitation created by the actuator, the vibration created by the hammer can be better detected by the sensors within a larger inspection area (Razi et al., 2013).

The sensors used to generate voltage signal under vibration were made by PZT-5H in a dimension of $25 \times 12 \times 1$ mm^3, and were set on the steel pipeline surface and closing bolted joints. During the signal processing step, the voltage signal was first de-composited as the intrinsic mode functions (IMFs). The extracted IMFs was then transformed to be a time-frequency representation of the original signal via the Hilbert-Huang transform (HHT). In the end, the empirical-based energy damage index (EMD_EDI) was calculated based on the energy stored in the associate signal of IMF. As a major result, this study confirmed the successful detection of the bolt loosening and its progression through utilizing the pulse generated by hammer and detected by PZT sensors (Razi et al., 2013).

The longitudinal waves generated by actuators can limitedly detect the cracks along the axial direction of pipeline. To more sensitively detect cracks in different directions on cylindrical structures, Cui et al. (2014) proposed one method which produced a first-order torsional wave by MFC transducers to replace the conventional longitudinal wave. During the experimental tests, three MFC transducers were attached on the surface of an aluminum pipe with a tilt angle of 45° to the axial direction. The dimension of the pipe was in a length of 2.4 m with an outer diameter of 102 mm. On one end of the pipe, a combination of one function generator (Tabor Electric WW1701) and one high-power amplifier (Trek PZD350A) were assembled to actuate MFC transducers via a 100 Volt peak-to-peak voltage signal. On another end of the pipe, an oscilloscope (YOKOGAWA DL1740) was connected with MFC transducers to collect the signals from those transducers (Cui et al., 2014), as shown in Figure 12. A digital signal acquisition system from National Instruments was also used to synchronize the generated and received signals for reducing the noise level and increasing the result accuracy. A proper range of operational frequency was set at 60~200 kHz to either prevent from wave overlapping or avoid a reduction of actuating capability from the MFC transducers. RMSD crack index with time of flight observed in residual signals were calculated based on both longitudinal and torsional wave signals. As expected, the measurement results based on torsional waves were more sensitive on longitudinal cracks than those based on longitudinal waves. The authors also emphasized that the location of MFC transducers still has room to be optimized for better detect and locate the cracks on cylindrical structures (Cui et al., 2014).

Figure 12 Experimental setup for using MFC transducers to generate torsional wave on health monitoring purpose (Cui et al., 2014).

The conventional bonding method between piezoelectric transducers and host structures for health monitoring purpose was using strong adhesive, such as epoxy or cyanoacrylate glue. However, to reuse the transducers or avoid conditions where direct sensor installation is not allowed, some studies proposed alternative methods to mount the transducers, such as using a magnetic coupling or a steel-wire coupling method. Da Silveira et al. (2017) compared the conventional mounting method (using cyanoacrylate glue) with the ones using magnet or steel wire on detecting loosening bolts. It was found that the conventional one was more sensitive to the damage than the other two methods, while the one using magnet had the lowest sensitivity against the damage (da Silveira et al., 2017). However, all those methods could be well sensitive to damages if a proper frequency range was used. Specifically, based on the results of RMSD and correlation coefficient deviation metric (CCDM), for magnetic mounting method, a narrow frequency band ranging from 54 to 150 kHz was recommended. This finding shows the potential of reusing and easy repositioning piezoelectric transducers or monitoring structures which are inaccessible (da Silveira et al., 2017).

Without actuators to actively vibrate the pipeline, Okosun et al. (2019) demonstrated that the piezoelectric-based health monitoring system could still perform the health monitoring function only based on the voltage outputs from sensors under vibration from fluid flowing. The sensor used in this output-only health monitoring system was made by PVDF (Okosun et al., 2019). Given the weak voltage output from PVDF, that study used one charge-to-voltage converter (also known as charge amplifier) to strengthen the voltage signal for further signal analysis. The pipe used in that study was steel one with length of 1 m, external diameter of 40 mm, and wall thickness of 2.5 mm. Three PVDF sensors were attached to different locations (closing to inlet, middle, and outlet) along the pipeline by a low viscosity epoxy. A data acquisition system, consisting of a NI USB 6002 DAQ with a NI LabView program, was used for storing and processing all voltage output information from PVDF sensors (Okosun et al., 2019). Under a steady flow rate, the voltage outputs from PVDF sensors on pipe with healthy status were first recorded for 5 min at a sampling rate of 2 kHz. Then, holes from 2 mm to 10 mm in diameter were created for different leakage conditions. As can be seen from Figure 13, the voltage outputs were clearly varied by leak states and healthy state of the pipeline. The voltage outputs from PVDF sensors then were recorded to further calculate the voltage-based leak index for quantifying the pipe health state. Based on the comparison between the leak indexes from those three sensors, the leakage location can be further roughly targeted (Okosun et al., 2019).

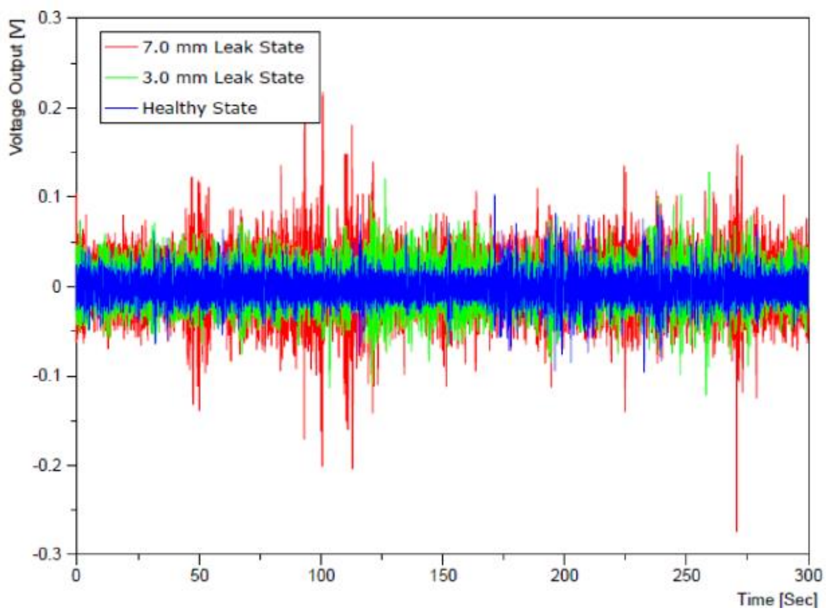


Figure 13 Example of voltage signal under healthy state and a number of leakage state of the pipeline (Okosun et al., 2019)

Raju et al. (2020) proposed a reusable non-bonded configuration of piezoelectric sensors on monitoring metal pipeline corrosion for saving the cost from piezoelectric sensors. The basic idea of that configuration was using two clamps to fix both ends of a piezoelectric strip on the pipeline. The PZT patch was made by PIC 151 in a dimension of $10 \times 10 \times 0.3$ mm^3. It was bonded at a center of an aluminum plate by epoxy resin. The entire surface of PZT patch was also coated by another layer of epoxy resin for protection against environmental effects. The corrosions on the pipeline was created by placing the pipeline in individual beakers filled with electrolyte (distilled water with 3.5% NaCl) and charged a constant DC of 18 V with current amounting 160 A/cm^2. RMSD was the major statistic technique for quantifying the corrosion on the pipeline. However, the detailed signal processing from the PZT patch was not described in that study. That study also stated that this non-bonded sensor configuration is also limited to be applied on small diameter pipelines with a thickness up to 2.5 mm (Raju et al., 2020).

2.5 Piezoelectric-based NDT with different signal processing methods

Instead of collecting the impedance or voltage signal from the piezoelectric transducers, the signals can be further processed to get more informative findings for health monitoring purposes, especially on the perspective of energy level (Cheraghi et al., 2005; Esmaeel et al., 2012). Although all studies mentioned in this section were on metal pipelines, those methodologies can be also implemented on plastic pipeline, but considering additional wave energy losses over distances due to the high damping from plastic material.

For selecting proper signal analysis method on the purpose of pipeline health monitoring by piezoelectric sensors, Cheraghi et al. (2005) used fast Fourier transform (FFT), wavelet transformation (WT), and wavelet packet transformation (WPT) methods separately to analyze the voltage signal from piezoelectric sensors for comparison purpose. All signal data used in this study was from numerical methods by finite element modeling (FEM) simulations. During the FEM simulation, the pipeline was excited by a concentrated load of 1000 N in a time interval of 2.5 μs. Piezoelectric sensors were made by BM500 (Navy Type II) PZT in a dimension of $0.05 \times 0.05 \times 0.001$ m^3. The tested pipeline was made by aluminum with length of 2 m, outside diameter of 273.5 mm, and wall thickness of 9.3 mm. The defects simulated in FEM were created by removing one-layer element within two rows in width of 100 mm. As a result, all those signal processing approaches were found able to detect pipeline defects with acceptable accuracy (as shown in Figure 14), while the incorporation of the WT and WPT methods could more accurately identify the pipeline defects with more visible differences observed.

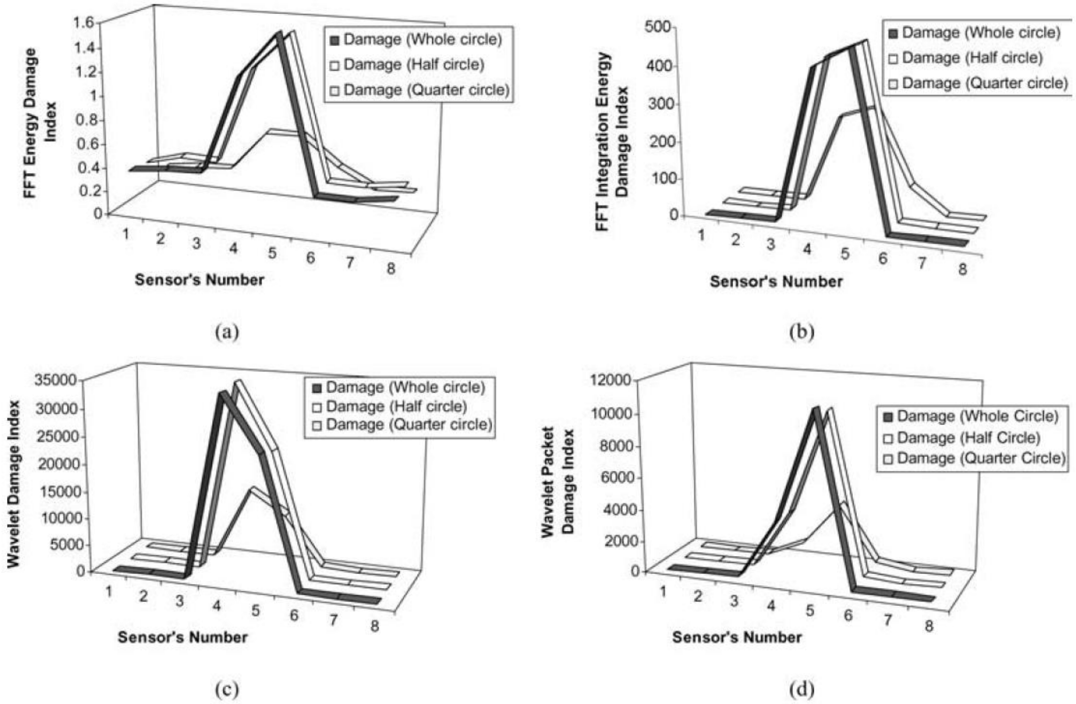


Figure 14 Comparison of different damage indices on detecting different damages on pipeline: a) the FFT; b) FFT integration; c) WT; d) WPT methods (Cheraghi et al., 2005).

Esmaeel et al. (2012) calculated an Energy Damage Index (EDI) based on voltage signals for health monitoring purpose on steel pipeline. PZTs were set on the bolts for detecting any loose on them, as shown in Figure 15. The PZT disks were PZT-5H from the Piezo Systems Inc. in a dimension of $24 \times 10 \times 1$ mm^3. Totally 6 PZT disks were respectively placed between 6 bolts on one joint. The excitation was from a piezoelectric impulse hammer, model 5800B5 from Dytran Instrument Inc. Five impacts were done at one testing location. The signals from PZT disks were collected by a multifunction PCI 6220 data acquisition card from National Instruments Inc (Esmaeel et al., 2012). As an output, the EDI was calculated via following steps: 1) a 0.25 s of signal was extracted from PZTs; 2) the signal was filtered using empirical mode decomposition (EMD) technique with Hilbert-Huang Transform; 3) after the signal was reconstructed, an intrinsic mode function (IMF) was established; 4) the energy of that IMF was then calculated; 5) the EDI in the end was calculated via the ratio of energy difference before and after damage occurs over the energy during health state. This alternative method of using EDI for health monitoring purpose can be a good option to monitor the bolt, while may be impractical to detect other damage types on the pipeline, which needs to be explored or modified in the near future for more comprehensive health monitoring ability (Esmaeel et al., 2012).

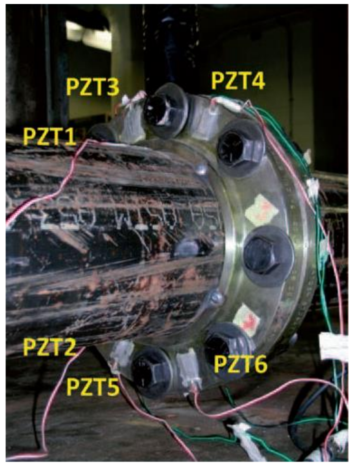


Figure 15 Details of the flange and sensor location and identification (Esmaeel et al., 2012)

The signal of impedance measurement within health monitoring system can have noises due to the influence of temperature, contact conditions between transducers and testing structures, and external loads. Those noises can make the absolute values of electromechanical impedance (EMI) inaccurately detect structure damages.

Martowicz et al. (2016) proposed and applied one outlier removal technique to process the raw impedance signal data for preventing from measurement errors caused by noises. Totally 30 frequency response functions (FRFs) for EMI were measured from undamaged pipeline as baselines, while additional 10 FRFs were measured from damaged pipelines (Martowicz et al., 2016). The Cross-Correlation Measure Damage Index was applied to get the most consistent damage index. Comparisons were done within all the FRFs taken from the same measurement condition to extract the outlier FRFs. Criterion was introduced to decide the outlier removal based on a metric, Mi. The analysis data was acquired from 12 PZT elements in total set on flanged pipeline components. Each PZT element was made by d31 Noliac piezoceramic material (NCE51) in a dimension of 15×15×0.3 mm3. The pipeline was made by steel, with internal and external diameters respectively of 27 mm and 33 mm. The diameter and the thickness of flange were respectively 100 mm and 11 mm. The impedance signals from PZT elements were collected by a AD5933 12-bit impedance analyzer (Martowicz et al., 2016). Two relevant health monitoring configurations were tests in this study. One relied on single PZT, which acted as either actuator or sensor. Another one required two PZTs, which acted as actuator and sensor separately. The specific FRFs were also different among those two configurations. The former was point FRF, while the latter one was transfer FRF. As a major result found from that study, the transfer FRF with the stochastic damage metric was preferred to be used for the health monitoring purpose on the pipeline (Martowicz et al., 2016).

3. Decision Making of Maintenance Planning for Plastic Pipeline

The facture failure of plastic pipeline due to degradation could be catastrophic, resulting in adverse economic, environmental, and social impact. Therefore, quantitative performance models of plastic pipeline are needed for planning of repair and replacement strategies. Currently, there are several lifetime prediction methods for plastic pipeline including: hydrostatic testing and standard extrapolation method, method based on Arrhenius equation, linear elastic fracture mechanics, and qualify method (Makris et al. 2019, Palermo, 2004; Khelif et al., 2007, Frank et al., 2019; Hutař et al., 2011; Zheng et al., 2020). However, these models are mainly deterministic and do not incorporate NDE data and the corresponding uncertainties.

The decision-making of maintenance planning is critical to ensure the integrity of plastic pipeline and is a continuous process during the entire service life. Such decision-making, however, is exceptionally challenging, as it involves many factors (such as budget, reliability of inspection data, environmental and loading impact, inspection and repair options) and needs consider tremendous amount of uncertainties (such as the inherent variability in environmental loading, material properties, material degradation mechanics, inspection data). In the decision making, different maintenance actions also need to be modeled quantitatively and appropriately, as their associate costs are different and they mitigate the risk at various degrees. To better prevent catastrophic failure of plastic pipeline, proactive repair strategy should be adopted considering the risk of failure, which includes fixed-interval and condition-based strategies.

Concerning optimizing decision variables (e.g., the next inspection time, the repair crack size criterion), one could set one or multiple objectives considering damage detection, cost, service life, and reliability. A few previous studies have decision making of maintenance planning for both plastic (Beaurepaire et al., 2012) and metal material (Liu and Frangopol, 2017; Zou et al., 2019; Kim et al. 2019) components.

Beaurepaire et al. (2012) optimized the maintenance scheduling of plastic mechanical components with a reliability-based method. Given the deterioration of the material properties with the fatigue crack growth, the stiffness of finite elements in simulation process shall be evolved. To count the stiffness changes during crack growth, the initial fatigue cracks with their further propagation were modeled via cohesive zone elements, with counting uncertainties inherent in material properties by means of random variables. The probability of detection was modeled based on the quality of inspection and the rack length changed by time (see Equation 3.1). They also did life cycle cost analysis associated with fracture, repair and inspection.

$$PoD(l(t,\theta),q) = 1 - \exp(-q \cdot l(t,\theta)) \tag{3.1}$$

Where, $l(t,\theta)$ is the crack length developed by time, t, with a vector of random variable, θ; q is the scalar value modeling the quality of inspection.

Liu and Frangopol (2017) developed the optimum inspection based on the utility of inspection information with the consideration of the attitude and preferences of decision makers toward the inspection outcome. The crack size on a steel structure was predicted by fatigue crack growth model with probabilistic parameters (as shown in Equation 3.2 and 3.3). Similar as the work done by Beaurepaire et al., the PoD was calculated for evaluating and comparing different NDT methods. But, the specific PoD function was slightly modified with standard normal cumulative distribution function (CDF) (as shown in Equation 3.4). The probability density function (PDF) of predicted crack size using random variables was then calculated and used to evaluate the information gained from inspection outcomes. Based on those predicted and inspected data, utility analysis was conducted to check the impacts of decision maker's attitude and preference on the inspection outcome. The maximum information gaining inspection plan was then made based on the utility value from utility analysis. The entire procedure proposed in that study to optimize the inspection schedule for maximum information gain was displayed in Figure 16.

$$\frac{da}{dN} = C\Delta K^m, \Delta K_{th} \leq \Delta K \leq K_{mat} \tag{3.2}$$

$$\Delta K = \Delta\sigma Y(a)\sqrt{\pi a} \tag{3.3}$$

$$PoD = 1 - \Phi\left[\frac{ln(a) - \lambda}{\beta}\right] \tag{3.4}$$

Where, a is crack size; N is number of cycles; da/dN is crack growth rate; C and m are material parameters; ΔK is stress intensity factor range; K_{mat} is material fracture toughness; ΔK_{th} is threshold value for the stress intensity factor range; $Y(a)$ is geometry function; $\Delta\sigma$ is stress range; λ is the location parameter; β is the scale parameter of the PoD curve in CDF, Φ is the standard normal CDF.

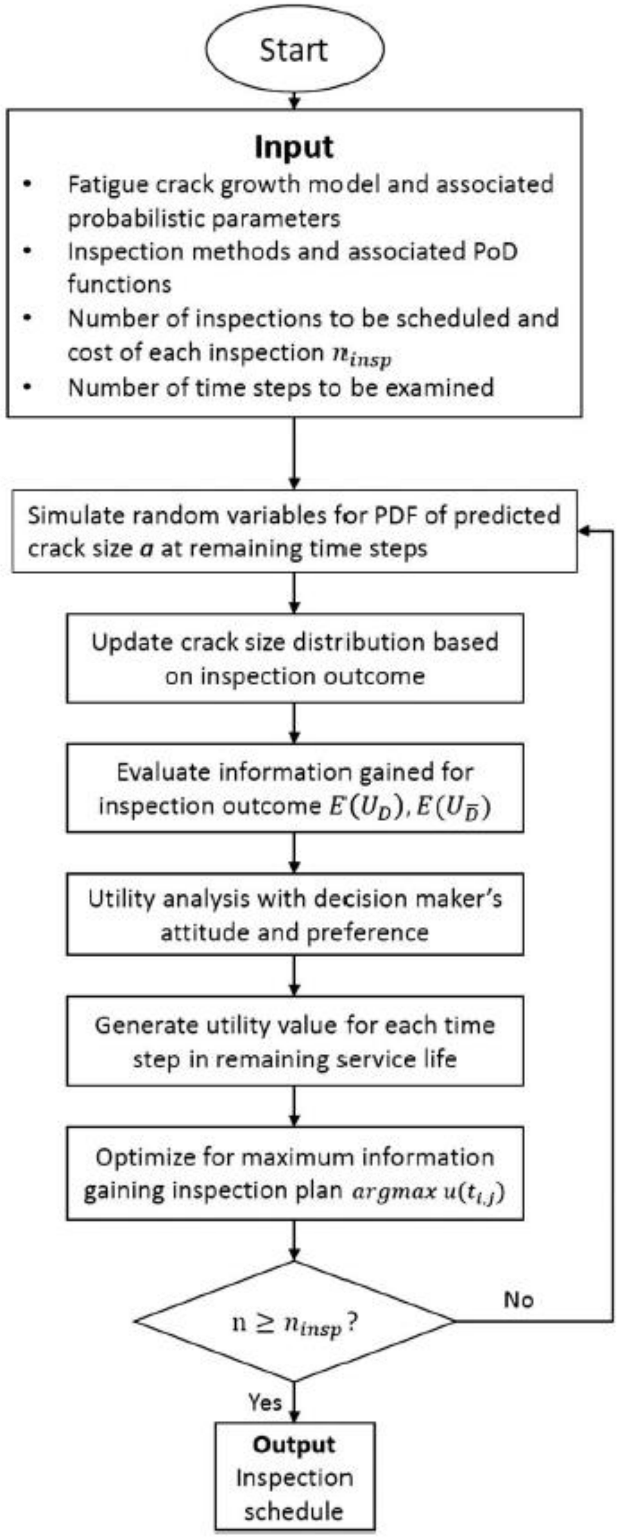


Figure 16 Flowchart for optimum scheduling of inspections for maximum information gain (Liu and Frangopol, 2017)

Zou et al. (2019) explored how to determine repair crack size criterion on steel structures using the expected lifetime cost and/or reliability as the optimization objective. Through applying an integrated probabilistic method combining crack growth, inspection modeling, and planning approaches, the optimum range for the repair criterion was derived to simultaneously meet the requirements on lifetime fatigue reliability and costs (Zou et al., 2019). The detailed processes used in reliability-based method and cost-based methods are displayed in Figure 17. For the specific techniques involved in either method, the probabilistic crack growth model was the same as the previous one used by Liu and Frangopol (as shown in Equation 3.2 and 3.3), counting uncertainty from input parameters, such as initial crack size, material parameter, stress range. For the probabilistic inspection modeling, the inspection uncertainty was calculated through a probability of detection (PoD) function with the mean detectable crack size and the specific crack size (as shown in Equation 3.5). The probabilistic planning approaches were based on decision tree analysis covering three levels (damage states, inspection results, and repair actions) (Zou et al., 2019).

$$PoD(a) = 1 - \exp(-a/E(a_d)) \tag{3.5}$$

Where, $E(a_d)$ is the mean detectable crack size.

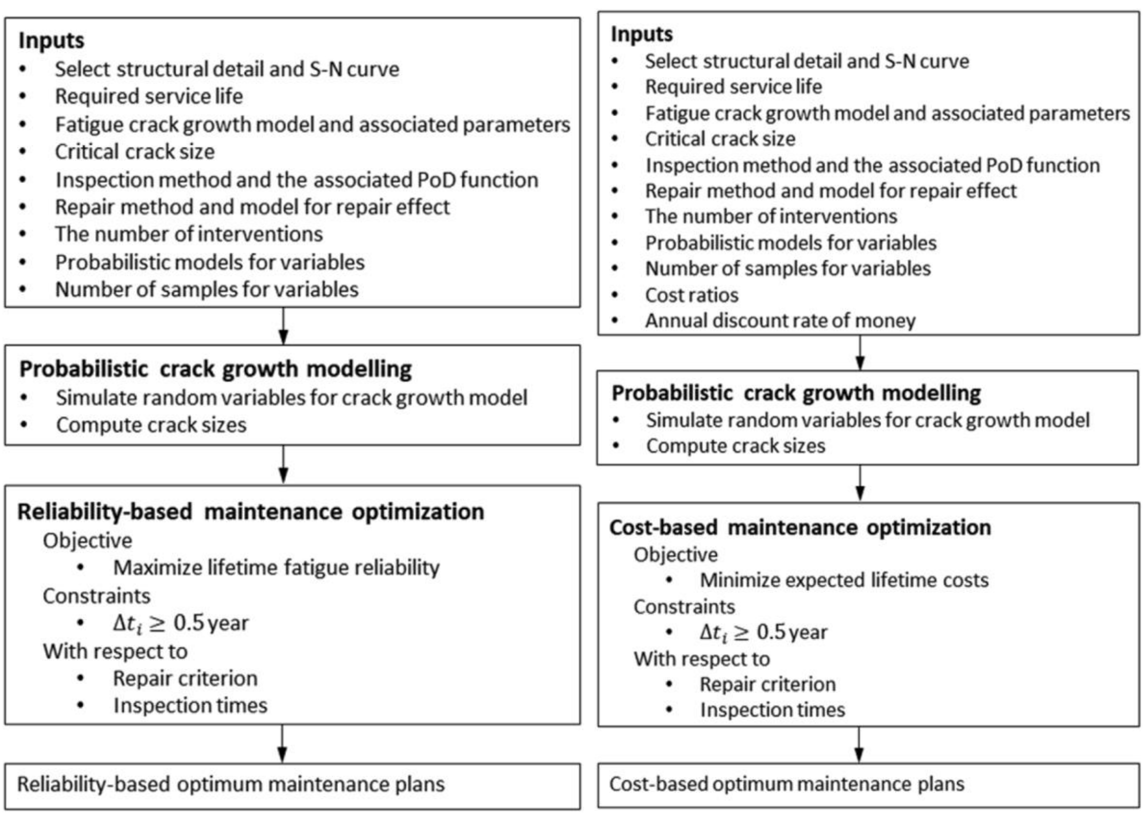


Figure 17 Flowchart of the probabilistic maintenance optimization approach (left: reliability-based; right: cost-based) (Zou et al., 2019)

Kim et al. (2019) determined maintenance planning strategy on steel structures by performing multi-objective optimization (MOOP) to minimize both the expected maintenance delay and the total inspection cost for fatigue-sensitive structures. The MOOP used in that study included two processes. The first process of MOOP was prior to damage (crack) detection for the purpose of determining the optimum inspection times. After the crack was detected during the optimum inspection schedule, the crack propagation was updated as inputs to second process of MOOP, aiming to optimize the maintenance schedule. The decision making was then determined according to the best Pareto solution from those two MOOPs. The detailed technical methods used in decision making process included the determining weight factors of the objects and multiple attribution decision marking (MADM). The entire proposed process was applied to a special case on an existing steel bridge (Kim et al., 2019). The entire procedure of optimum inspection and maintenance plan based on continuously updated inspection information was displayed in Figure 18.

As a major finding from that study, it was confirmed that the crack size changed by time could continuously affect the further crack propagation. With the increased crack size, the material parameter and the stress range were increased, and the crack propagation was accelerated. This finding reflects that timely inspection on crack propagation will be extremely helpful for making decisions on maintenance with more accurate cost estimations. That study also compared different MADM methods, including the simple additive weighting method (SAW), the technique for order preference by similarity to ideal solution (TOPSIS), and the elimination and choice expressing the reality (ELECTRE). As another key conclusion from that study, it was found that, compared to the SAW and TOPSIS methods, the ELECTRE method in both MOOP processes resulted in shorter damage (crack) detection delay but more inspection costs (Kim et al. 2019).

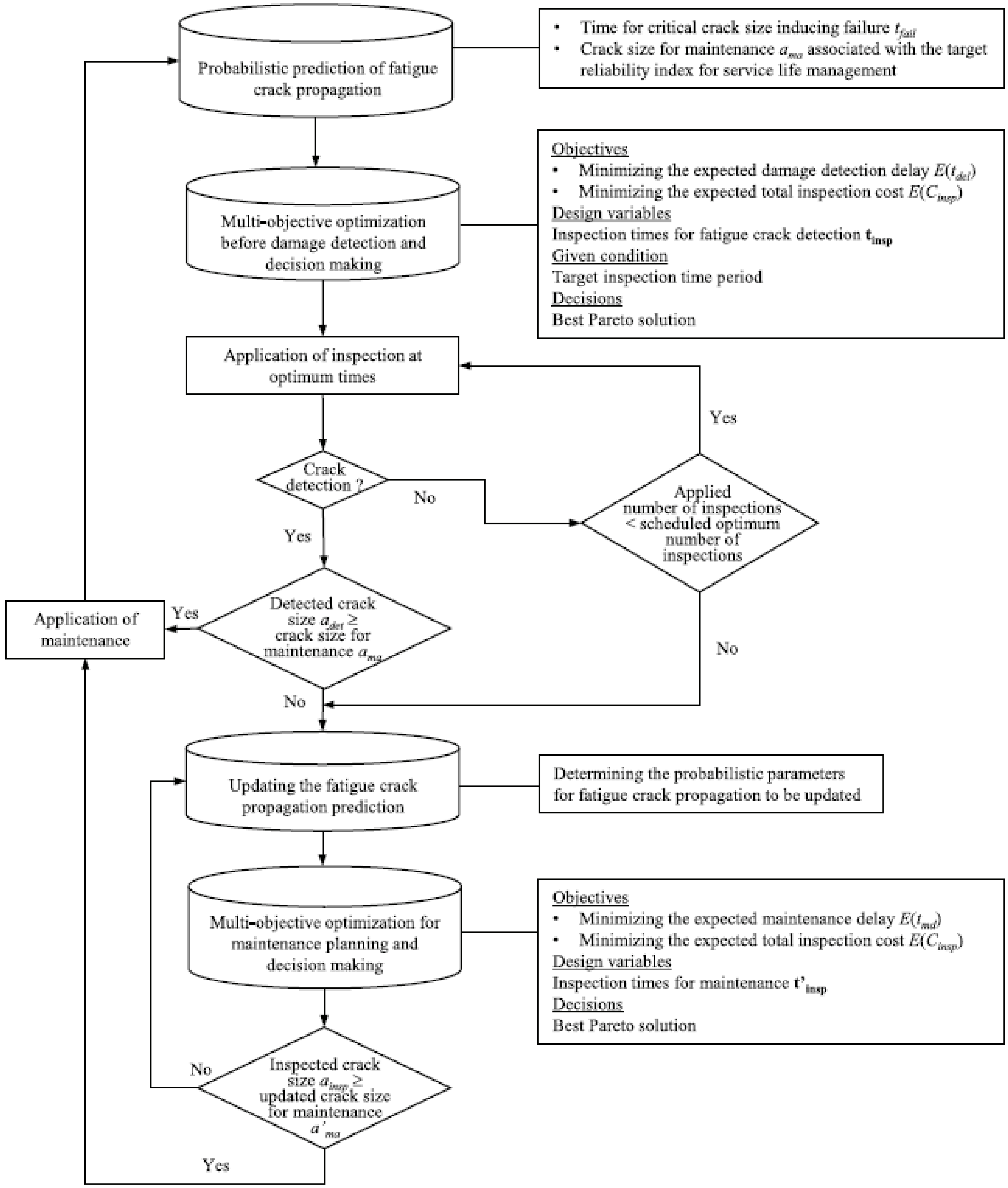


Figure 18 Flowchart of optimum inspection and maintenance plan based on continuously updated inspection information (Kim et al. 2019).

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